Assessing possible thermal rearing restrictions for juvenile coho salmon (*Oncorhynchus kisutch*) through thermal infrared imaging and in-stream monitoring, Redwood Creek, California

M.A. Madej, C. Currens, V. Ozaki, J. Yee, and D.G. Anderson

Abstract: We quantified patterns in stream temperature in a northern coastal California river using thermal infrared (TIR) imaging and in-stream monitoring and related temperature patterns to the historical and present distributions of juvenile coho salmon (*Oncorhynchus kisutch*). In Redwood Creek, California, water temperature increased from the headwaters to about 60 km downstream, then gradually decreased over the next 40 km as the river approaches the Pacific Ocean. Despite the lack of fish migration barriers, juvenile coho are currently only observed in the downstream-most 20 km, whereas historically they were found in 90 km of river channel. Maximum daily temperatures and duration of elevated stream temperatures were not significantly different in the headwater and downstream reaches but were significantly higher in the 50 km long intervening reach, where maximum weekly maximum temperatures ranged from 23 to 27 °C. An increase in stream temperatures in the middle basin during the last three decades as a result of channel aggradation, widening, and the removal of large riparian conifers may play an important role in restricting juvenile coho to one-fifth of their historical range.

Résumé : Nous avons mesuré quantitativement les patrons de température dans une rivière côtière du nord de la Californie à l'aide d'imagerie thermique infrarouge (TIR) et d'enregistrements de température dans les cours d'eau et nous avons relié ces patrons thermiques aux répartitions passées et actuelles des jeunes saumons coho (*Oncorhynchus kisutch*). Dans Redwood Creek, Californie, la température augmente depuis l'amont sur environ 60 km vers l'aval, puis elle baisse graduellement sur les prochains 40 km alors que la rivière s'approche du Pacifique. Malgré l'absence de barrière à la migration des poissons, les jeunes saumons coho s'observent actuellement seulement dans les 20 km les plus en aval, alors que dans le passé ils se retrouvaient sur 90 km du cours de la rivière. Les températures journalières maximales et la durée des températures élevées ne diffèrent pas significativement dans les sections d'amont et d'aval, mais elles sont significativement plus élevées dans la section intermédiaire de 50 km, où le maximum des températures maximales hebdomadaires varient de 23 à 27 °C. Un accroissement de la température dans le bassin moyen de la rivière au cours des trois dernières décennies à cause de l'aggradation du chenal, de l'élargissement du lit et de l'enlèvement des grands conifères de la rive peut jouer un rôle important dans la restriction des jeunes saumons coho à un cinquième de leur aire de répartition historique.

[Traduit par la Rédaction]

Introduction

Water temperature is an important physical factor that regulates the distribution of fish (Li et al. 1994; Welsh et al. 2001). High water temperatures have been shown to limit the distribution of salmonids within streams (Meisner 1990), reduce abundance (Ebersole et al. 2001), and fragment populations within a watershed (Matthews and Zimmerman 1990). Elevated water temperatures can also decrease growth and increase juvenile mortality (Brett 1979). High water temperatures can negatively influence salmonid egg development and juvenile appetite and growth (Dockray et al. 1996), as well as negatively alter behavior and interspecies interactions (De Staso and Rahel 1994; Beschta et al. 1987).

Coho (or silver) salmon (*Oncorhynchus kisutch*) juveniles, like most salmonids, prefer cool-water rearing and typically reside in the stream for a minimum of 1 year after hatching. However, in Prairie Creek, a tributary to Redwood Creek in

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northern coastal California, about one-quarter of the smolts reside in-stream for 2 years before migrating to the Pacific Ocean (Bell 2001) so they are especially vulnerable to stressful summer temperatures. Redwood Creek is currently listed as temperature- and sediment-impaired under the Clean Water Act, section 303d, because of past timber harvest, removal of riparian vegetation, widespread streamside landsliding, and channel aggradation. The upstream reach of the river is beginning to recover from past damage in terms of pool frequency and depth (Madej 2001). A recent reconnaissance-level assessment of fish habitat in the upper reach of Redwood Creek indicates that the aquatic habitat (high pool frequency, extensive shading from alders, a moderate channel gradient (0.5%), and adequate spawning gravel size) should now support salmonids (California Resources Agency 2005); nevertheless, coho salmon are absent.

Juvenile coho salmon distribution in the Redwood Creek basin is presently limited to the downstream-most 20 km of mainstem and a few large low-gradient tributaries in the lower basin, but historically coho were found throughout most of the mainstem of Redwood Creek (Snyder 1931). This apparent lack of coho in upper Redwood Creek under present conditions is puzzling, and we hypothesize that the summer thermal environment on Redwood Creek restricts juvenile coho rearing for most of the mainstem length. To evaluate this concern, Redwood National and State Parks and the US Geological Survey (USGS) initiated a study in 1997 to document the basin-wide summer water temperature regime of Redwood Creek using continuous-recording temperature probes. This effort provided in-stream and air temperature data at several locations along Redwood Creek. To supplement this study, an airborne thermal infrared (TIR) survey was conducted in the summer of 2003 to provide a longitudinal profile of spatially continuous water temperature data for Redwood Creek. The objectives of this multi-scale study were (*i*) to determine longitudinal trends in summer water temperature (maxima, minima, and durations of elevated temperatures), (*ii*) to compare temperature regimes in the stream reach bearing coho with those in the reach not bearing coho, and (*iii*) to identify warm reaches of Redwood Creek that may be limiting thermal environments for rearing coho.

Materials and methods

Study site description

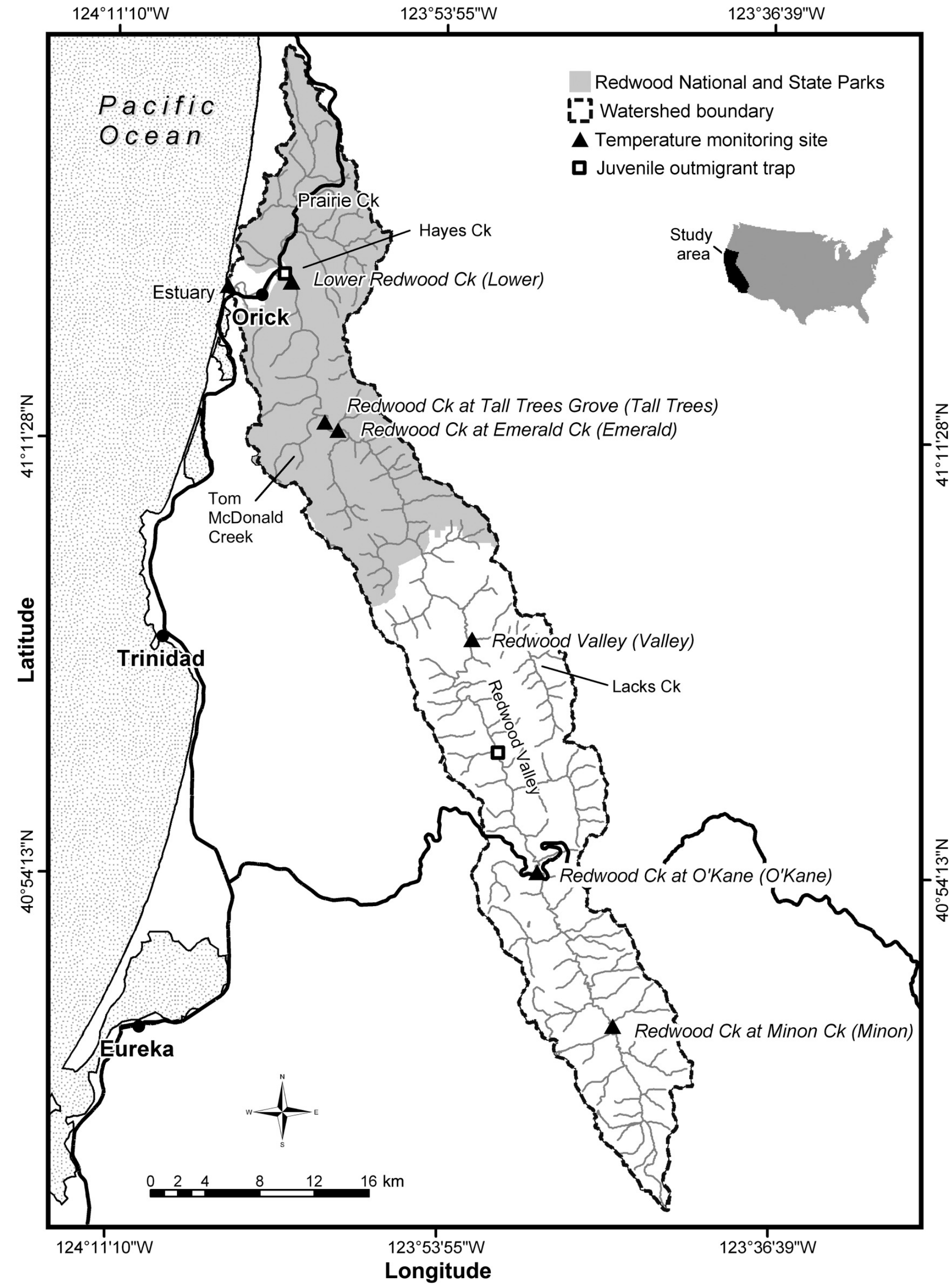
Redwood Creek drains an area of 738 km^2 in northern coastal California and enters an estuary at Orick, California (Fig. 1). The basin receives an average of 200 cm of rainfall annually, most of which occurs between October and March. In the upstream-most 72 km, the river flows through privately owned lands primarily under timber management, and in the lower 36 km, it flows through Redwood National and State Parks (RNSP). Except for a steep, 10 km long reach in the headwaters of the basin, channel gradient in Redwood Creek is less than 2% and averages 0.3% (Madej 1995). There are no barriers to fish migration for 100 km of the mainstem. Median particle size (D_{50}) decreases from 40 mm near Minon Creek to 16 mm at Orick.

Aerial photographs from 1936 and 1947 show that before commercial timber harvesting, Redwood Creek was narrow and sinuous in most reaches and covered with a thick canopy of coniferous trees. Large-scale timber harvesting began in the basin in the 1950s. By 1966, 55% of the forest had been logged, and by 1992, ~80% of the basin had been logged (Best 1995). Large floods in 1953, 1955, 1964, 1972, 1975, and 1997 initiated widespread road and stream-crossing failures, gullying, and streamside landsliding in the basin. The floods before 1997 caused extensive channel aggradation and bank erosion throughout Redwood Creek, although channel changes were most extensive in the upper basin, where logging activity had been the most intense. Aerial photographs and field observations documented that the channel widened, pool size and frequency diminished, channel bed material became finer, and the channel bed aggraded up to 9 m at some sites (Madej 1995). Concomitantly, the dominant riparian vegetation changed dramatically. In 1948, 86% of the length of the riparian zone along Redwood Creek was dominated by conifers, which decreased to 15% by 1997, with canopy density decreasing as well (Urner and Madej 1998). Most of the intact old-growth conifer riparian zones are located on the downstream-most 20 km of Redwood Creek within RNSP.

This transition from a riparian zone dominated by old-growth redwood and Douglas fir to brush or smaller hardwoods (primarily red alder, *Alnus rubra*) presumably increased water temperatures in Redwood Creek, but few data are available to assess time trends. Interviews with long-time residents living in the middle basin of Redwood Creek provide anecdotal evidence of summer water temperature in the early to mid-20th century. All remember that the water in Redwood Creek used to be like “ice” when they were kids, but the river is warmer today (Van Kirk 1994). They also described Redwood Creek as having a thick canopy of trees. Between 1953 and 1959, average daily maximum of water temperature in July and August in this area was 22 °C, based on periodic measurements at the USGS O’Kane (or “near Blue Lake”) stream gaging station (Blodgett 1970). In contrast, from 1975 to 1980, the station recorded daily water temperatures that exceeded 28 °C on average 7 consecutive days per year. Annual peak water temperatures were between 29 and 32 °C for that time period (USGS 1975–1980).

The fish fauna of Redwood Creek is typical of the coastal streams of northern California (Anderson 1988; Brown 1988). Both anadromous and resident fish species are present in the basin and include coho and Chinook (*Oncorhynchus tshawytscha*) salmon, steelhead (*Oncorhynchus mykiss*) and coastal cutthroat (*Oncorhynchus clarkii*) trout, lamprey (*Lampetra tridentata*), sculpins (*Cottus* spp.), and stickleback (*Gasterosteus aculealus*). Anecdotal evidence, including interviews with local residents, photographs, and newspaper articles, provides some evidence of coho along the length of Redwood Creek (Anderson 1988; Van Kirk 1994; James O’Barr, RNSP, P.O. Box 7, Orick, CA 95555, USA, unpublished data). In addition, limited scientific observations (Briggs 1953; California Department of Fish and Game (CDFG) 1965, 2002) portray historical distribution of coho throughout most of the Redwood Creek basin. Snyder (1931) reports that the middle basin of Redwood Creek was

Fig. 1. Redwood Creek watershed in California, USA. Continuous in-stream data loggers were deployed in the main flow of Redwood Creek at each of the monitoring sites.



used as a silver salmon egg source for a Trinity River hatchery in the mid- to late 1890s. Hallock et al. (1952) described mainstem Redwood Creek as an "excellent silver salmon stream" with pools too deep to seine.

During the last 25 years, however, coho distribution has become much more limited. In 1997, coho salmon were federally listed as threatened in the Southern Oregon/Northern California Evolutionary Significant Unit, where Redwood Creek is located. A combination of direct observation (snorkel surveys), spawning surveys, and downstream migrant trapping has been used to document fish presence in various reaches of Redwood Creek. In 1980–1981, Brown (1988) and Anderson (1988) surveyed the entire Redwood Creek basin for fish presence. Adult spawning surveys were conducted on the mainstem in the middle basin of Redwood Creek during the winters of 1989 and 1990. During the summer of 2003, RNSP fishery biologists surveyed juvenile coho "presence–absence" using direct observation by snorkeling the downstream half of Redwood Creek (Lacks Creek downstream to Hayes Creek). The CDFG operates two downstream migrant traps, one in the middle basin at river kilometre 53 (rkm 53, Redwood Valley) and the other in lower Redwood Creek (rkm 6.5, “Lower”). Traps typically operate from March until late July, when juvenile Chinook outmigration slows significantly.

Juvenile coho salmon temperature requirements

Juvenile coho salmon require cool water to survive and grow and are susceptible to increased summer water temperatures because they rear in freshwater for at least a year. The estimated upper lethal temperature for juvenile coho varies depending on the techniques used. Brett (1952) reported that when five species of Pacific salmon, including coho, were exposed to various temperature gradients, all juvenile salmonid species preferred temperatures between 12 and 14 °C and juveniles generally avoided stream temperatures above 15 °C. He also reported 26.0 °C as the upper lethal temperature based on the incipient lethal temperature. In this test, fish were acclimated at 20 °C before being placed into higher temperature water. However, because of an accidental loss of coho during the experiment, he based his findings on the upper thermal limits of spring Chinook salmon. Becker and Genoway (1979), as referenced in Bjornn and Reiser (1991), reported 28.8 °C as the upper lethal temperature based on the critical thermal maximum technique in which the water and fish were slowly heated. Using the same technique, McGeer et al. (1991) determined that juvenile coho survived at temperatures up to 23 °C, but none survived at water temperatures higher than 25.5 °C.

In the absence of lethal effects, stream temperature can still influence the distribution and growth of juvenile salmonids. For a nearby northern California basin, Welsh et al. (2001) reported that juvenile coho were not present in streams where the maximum weekly maximum temperature (MWMT) exceeded 18.1 °C or where the maximum weekly average temperature (MWAT) exceeded 16.8 °C. Growth stops when water temperatures exceed 18–20.3 °C (Stein et al. 1972; Bell 1973; Armour 1991). Many factors, such as food availability, habitat quality, and competition, as well as water temperature, affect salmonids. Willey (2004) modeled bioenergetics of juvenile coho salmon in northern California streams and concluded that in streams with limited food resources, juvenile coho growth may decrease as daily average temperatures increase above 15.7 °C. Because no clear temperature thresholds have been established regarding coho health, in this study we compare ranges of temperatures, as well as maximum temperatures, in various stream reaches.

Stream temperature monitoring

Two types of temperature monitoring were used in this study to provide multiscale information: ground-based measurements and remote-sensing techniques. In-stream data loggers measured summer stream temperatures at point locations along Redwood Creek for 5–7 consecutive years. Remote-sensing techniques using TIR imagery provided a spatially continuous longitudinal profile of surface water temperature at a given point in time. Thus the two methods are complementary in assessing both spatial and temporal trends in the water temperature regime.

Data loggers (Onset Computer Corporation, Bourne, MA 02532, USA) collected continuous water temperature data at seven sites along Redwood Creek during the summers of 1997–2003 (Fig. 1). We selected sampling sites based on study objectives and available stream access. Data loggers were calibrated before use and were deployed from June through September with sampling intervals that ranged from 15 to 60 min. Stream data loggers were submerged in the water column in areas of shade and mixed water. At a subset of stream study sites, we placed air temperature data loggers in a shaded area of the riparian zone in close proximity to the stream data logger. Cool air temperature is a reliable indicator of fog presence during summer months (and consequently less solar radiation is reaching the stream on those days). The accuracy of the probes is ±0.2 °C, and the resolution is ±0.2 °C.

On 29 July 2003, a helicopter flight surveyed 95 km of Redwood Creek by collecting TIR and color video imagery of Redwood Creek and its riparian zone from a flight altitude of 425 m above ground level. Visible-band and TIR (8–12 μm) cameras attached to a gyro-stabilized mount on the underside of the helicopter collected 2500 images. The TIR data captured water temperatures at midafternoon when stream temperatures reached their daily maximum. The contractors recorded TIR images directly from the sensor to an on-board computer, and individual images were referenced with time and position data provided by a global-positioning system (Watershed Sciences Inc. (WSI) 2004). They converted measured radiance values contained in the raw TIR images to surface water temperatures based on the emissivity of water, atmospheric transmission effects, ambient background reflections, and the calibration characteristics of the sensor. They then compared the radiant temperatures with the temperatures measured by 11 in-stream data loggers. Calibration parameters were fine-tuned to provide the most accurate fit between the radiant and in-stream temperatures. The average absolute differences between the temperatures recorded by the in-stream data loggers and the radiant temperature derived from the TIR images were within the desired accuracy of 0.5 °C (WSI 2004).

Once the TIR images were calibrated, WSI interpreted stream temperatures for each of the 2500 images by determining the radiant temperature (pixel values) of 10 points along the center of the stream channel. The temperature value for each thermal image was estimated by using the median value of the 10-point sample. The temperatures of detectable surface inflows (e.g., surface springs, tributaries) were also sampled. In some cases, tributaries or other features detected in the imagery were not sampled because of their small size. In addition, data processing focused on interpreting spatial variations in surface temperatures observed in the images. The images were assigned a distance based on a 1:24 000 routed GIS (geographic information system) stream coverage obtained from the National Park Service, Arcata, California. The median temperatures for each sampled image were then plotted against the corresponding river kilometre to develop a longitudinal temperature profile (WSI 2004). The location and median temperature of all sampled surface water inflows were also mapped to illustrate how these inflows influence mainstem temperature patterns.

Variable water surface conditions (such as riffle versus pool), slight changes in viewing aspect, and variable background temperatures (e.g., sky versus trees) can result in differences in the calculated radiant temperatures within the same image or between consecutive images. The apparent temperature variability is generally less than 0.6 °C (Torgerson et al. 2001). In general, apparent stream temperature changes of <0.6 °C are not considered significant unless associated with a tributary or other source.

Data analysis

We used several metrics to define temperature regimes and compare stream temperatures at various locations along Redwood Creek: daily maxima and minima, weekly average maxima (MWAT and MWMT, defined below), duration of exceedance of a given temperature, and number of consecutive hours over specific high temperatures ("stress intervals"). MWAT was originally defined by Brungs and Jones (1977) as a limit to the maximum temperature, for a species and life stage that should not be exceeded in a regulatory sense, but more recently MWAT is the term used to describe the maximum value of a 7-day moving average of daily average temperatures (Welsh et al. 2001). This latter usage is the definition used in the present study. Similarly, MWMT is the maximum value of a 7-day moving average of daily maximum temperatures.

Cumulative frequency–distribution curves illustrate the percentage of time that a stream temperature was exceeded for each monitoring site for the critical period of 1 July to 31 August when stream temperatures are highest. These curves are useful indicators of the seasonal exposure to high temperatures, but they do not indicate if thermal recovery (periods of time <18 °C) occurred at night. Thermal recovery, if present, would help ameliorate temperature stress on fish. To examine the daily stress levels more closely, we defined "stress intervals" by the number of consecutive hours that a particular temperature was exceeded during July and August in 2000–2003. For example, if on 2 July, a probe recorded 10 consecutive hours of >18 °C, a 10-h stress interval of >18 °C would be counted for that date. Stress intervals were computed for consecutive hours >18 °C, >20 °C, >22 °C, and >24 °C for all sites. We compared the mean duration and frequency of stress intervals for these temperature values among sites.

Statistical analyses

Differences in daily maximum and minimum temperatures for July and August 1997 to 2003 among sites were analyzed using a repeated-measures analysis of variance model to account for temporally correlated daily measurements from the same site that might undermine the independence of the data (PROC MIXED, SAS Institute Inc. 1999). We modeled temporal correlations using various correlation types, including no correlations, and Akaike's information criterion (AIC) was used to select the correlation type corresponding to the best-fitting model (lowest AIC value) (Littell et al. 1996; Burnham and Anderson 1998). We assumed temperatures from different years to be temporally independent, and a year effect was included in the model to account for any variation associated with year differences. Temperatures from different sites on the same day were considered spatially correlated, therefore the data were converted into pairwise differences between sites to isolate site-related differences and eliminate any shared spatial effects between sites. We determined differences among sites by statistically testing the null hypothesis that all paired difference data had a mean of zero. The data were fitted to an ANOVA model containing site pair, year, and interaction effects, and the interaction was removed if not found to be significant. All tests were conducted at $\alpha = 0.05$ significance level.

We compared multiple pairs of sites by using an approach adapted from Fisher's protected least significant difference (LSD) tests. We first determined whether the F test for pairings indicated an overall significant difference among sites. If the F test was significant, then we used individual t tests to determine which mean paired differences between sites were statistically different from 0. If the F test was not significant, then no differences were concluded and no individual t tests were conducted.

Similar to the analysis of daily maxima data, the daily minima and the stress durations at each of the four temperature values were compared across sites using a repeated-measures ANOVA followed by pairwise comparisons based on Fisher's protected LSD tests. We log-transformed stress durations before analysis to remove skewness. Because a long stress interval at one site could occur in association with either a long interval or two short intervals at a nearby site, we did not model any spatial correlations in the durations of stress intervals between sites. We determined differences among sites by statistically testing the null hypothesis that all sites had equivalent mean durations of stress intervals.

Results

Fish observations

Recent surveys and trapping efforts document that juvenile coho salmon are currently limited to the downstream-most 20 km of Redwood Creek and tributaries entering that reach. In the 1980–1981 survey of the entire Redwood Creek basin, only three tributaries in the middle basin had single observations of juvenile coho (Brown 1988), and only a handful of tributaries in the lower basin contained rearing juvenile coho (Anderson 1988). Although spawning surveys are difficult to conduct because of low visibility and high stream flow during the winter, the 1989 surveys documented several adult coho salmon in the middle basin of Redwood Creek. Adult coho salmon spawners were observed in Redwood Valley during the winter 2000–2001 spawning season (Pacific Coast Fish, Wildlife and Wetlands Restoration Association 2002); however, a downstream migrant trap located in the middle basin of Redwood Creek (rkm 53) has never captured a juvenile coho in the past 5 consecutive years of trapping (Sparkman 2005). Juvenile coho were captured at the lower trap (rkm 6.5) in 2003 and 2004. In 2003, unusually high flow conditions early in the season made the lower trap inoperable for several weeks and low juvenile coho numbers precluded determining population estimates (Bill Pinnix, US Fish and Wildlife Service, 1655 Heindon Road, Arcata, CA 95521, USA, personal communication). Only 29 young-of-the-year (YOY) and 12 age-1+ coho were trapped in 2003. In 2004, 202 YOY juvenile coho and 69 age-1+ coho salmon were caught at the lower trap (Sparkman 2004). During the summer of 2003, RNSP biologists conducted an extensive juvenile coho "presence–

Fig. 2. Average daily maximum stream temperatures measured in Redwood Creek at O'Kane for two time periods: 1975–1980, solid line; 1998–2003, broken line.

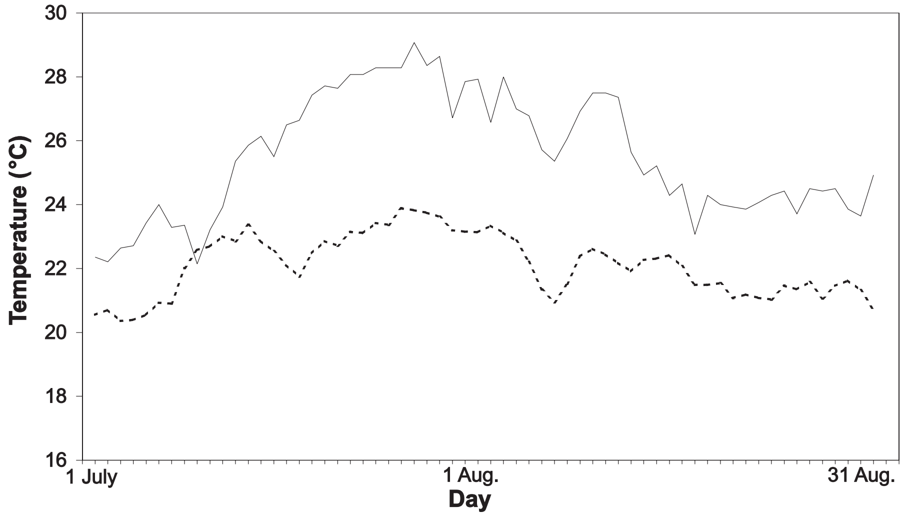


Table 1. Means and standard deviations (SD) of daily minimum and maximum temperatures for period of record (1 July to 31 August 1997 to 2003).

	Daily temperature (°C)	
Redwood Creek site	Mean minimum ± SD	Mean maximum ± SD
Estuary	17.0±1.2c	18.9±1.2a
Lower	16.1±0.6b	20.6±1.4b
Tall Trees	18.3±0.8d	21.9±1.1c
Emerald	18.3±0.8d	22.2±1.2c
Valley	18.3±1.1d	24.6±1.9d
O'Kane	17.3±1.4c	22.3±1.6c
Minon	14.5±1.5a	20.0±1.5b

Note: Sites not sharing a common letter were statistically different from one another ($p < 0.05$). Sites with increasing temperatures are classified by alphabetically increasing letters.

absence" snorkel survey on the lower half of Redwood Creek, including areas along the channel margins such as undercut banks and side pools. No coho were observed in the main channel above rkm 20 (Tom McDonald Creek), and juvenile coho were only observed in nine locations in the lower 20 km of channel (Ozaki and Anderson 2005). Of the few juvenile coho sighted in Redwood Creek, seven of the nine locations were side pools. Side pools were separated from the main channel by a gravel bar but were open to Redwood Creek on the downstream end. Many of the pools were influenced by cool seeps and springs, intragravel flow, groundwater, or small tributaries. These pools were generally cooler than the mainstem. The other two mainstem sightings were at the downstream end of the surveyed reach, near the coast.

Daily maximum temperatures

During a period of channel aggradation in upper Redwood Creek from 1975 to 1980, average daily stream temperatures at O'Kane were very high (Fig. 2). Maximum daily temperature data were not available from 1980 to 1998, but the period from 1998 to 2003 exhibited a considerable decrease in average daily maxima. Presently the peak temperatures of 22–24 °C are comparable with the 22 °C peak measured between 1953 and 1959.

Based on the recent data set, average daily maximum temperatures were similar in the uppermost and downstream reaches of Redwood Creek but were higher in the middle basin (Table 1). A model based on temporal correlations exponentially declining over days was found to have a superior fit compared with a model assuming no temporal correlations (AIC difference = 1318). There were no statistical differences between lower Redwood Creek (coho-bearing reach) and the Minon reach (no coho present) (20 °C and 20.6 °C, respectively). In contrast, sites in intervening reaches (Tall Trees, Emerald, Valley, and O'Kane) had significantly higher daily maximum temperatures, averaging over 21 °C, with Valley exhibiting the highest value (24.6 °C).

Daily minimal temperatures

In addition to maximum daily stream temperatures, we were interested in how the stream thermally recovers at night, and so we examined the minimum daily temperatures. Upper Redwood Creek (Minon) is the coolest site in terms of mean daily minimum temperatures, and the middle basin sites (Tall Trees, Emerald and Valley) are the warmest (Table 1). If we examine the daily pattern of minima more closely, some interesting differences in thermal patterns in Redwood Creek appear (Fig. 3). Using 2003 as an example, we show that at the Minon site, temperatures dropped below 18 °C on

Fig. 3. Daily minimum temperatures recorded in July and August 2003. These patterns were typical of all the years studied. Bold horizontal line represents the 18.1 °C threshold of concern for coho (Welsh et al. 2001).

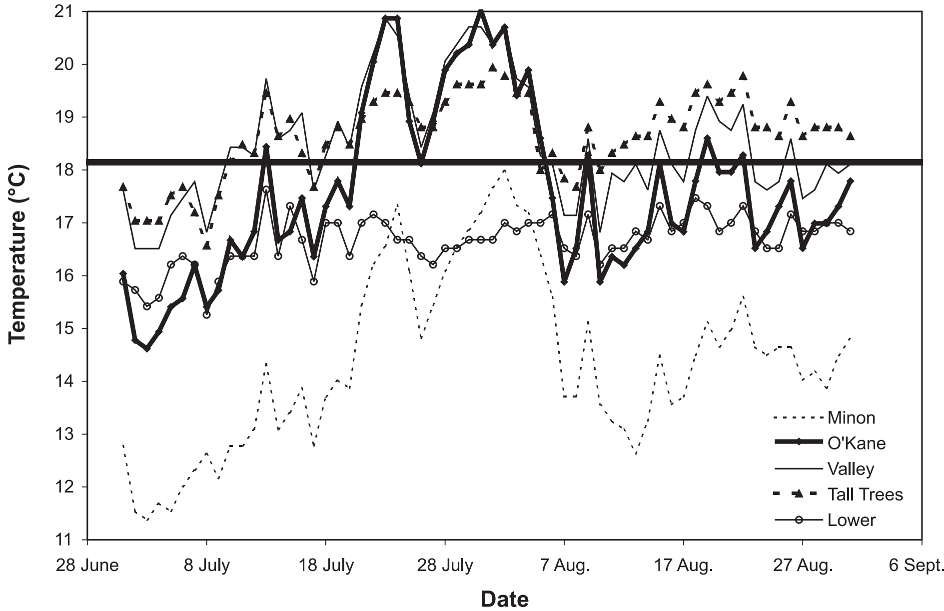


Table 2. Maximum weekly average temperatures (MWAT) at Redwood Creek monitoring stations.

			MWAT (°C)						
Redwood Creek site	Drainage area (km^2)	Distance to mouth (km)	1997	1998	1999	2000	2001	2002	2003
Estuary	730	0.3		19.1	17.4	18.4	18.9	18.7	20.2
Lower	611	7.7			17.6	18.5	18.2	18.1	18.7
Tall Trees	533	22.0		21.0	19.7	21.0	20.8	20.4	21.2
Emerald	520	23.3					20.9	20.5	21.3
Valley	314	46.7	22.0	22.3		22.1	21.9	21.8	22.5
O'Kane	175	72.9	21.4	21.7	20.1	21.4	21.0	21.4	22.2
Minon	86	91.0	18.4	18.5	17.6			18.3	19.0
Valley (air)*			28.7	27.9	25.7	25.6	27.7	29.8	29.3

Note: All MWAT records occurred in July or August of their respective year. Temperatures were not recorded at all stations for every year of the study. MWAT is the maximum of a 7-day moving average of daily average temperatures.

*Mean daily maximum air temperature for 1 July – 31 August.

each day for the entire summer season. Valley and O'Kane exhibited the highest values for minimum daily temperatures in late July and early August 2003. However, by 7 August, those reaches showed greater cooling at night than the downstream reach of Tall Trees. Even though the Tall Trees reach is within the old-growth redwood forest, daily minimum temperatures remained above 18 °C for most of the summer. Not until Lower were minimum daily temperatures consistently below 18 °C. These data indicate that at least half the length of Redwood Creek (Tall Trees to O'Kane, 50 km) had daily minimum temperatures above the desired range for coho. Lower also showed a more subdued pattern in terms of seasonal variation (Fig. 3). This reach has the highest discharge (so greater thermal mass) but also has more frequent coastal fog than upstream reaches.

A model based on temporal correlations exponentially declining over days was found to have a superior fit compared with a model assuming no temporal correlations (AIC difference = 1541). The daily minimum temperatures between the uppermost and downstream reaches of Redwood Creek were dissimilar, with the Minon site at the uppermost reach having lower minimum temperatures than lower Redwood Creek (Table 1). Stations in intervening reaches (Tall Trees, Emerald, and Valley) had significantly higher daily minimum temperatures, averaging >18 °C.

Maximum weekly average and maximum weekly maximum temperatures

Water temperatures reached their summer maxima in late July or early August for all years of record. MWAT and MWMT show similar patterns throughout Redwood Creek (Table 2; Fig. 4). Overall, the summer of 1999 exhibited the lowest MWAT values for all monitoring sites, as well as one of the coolest average air temperatures. Redwood Valley (Valley), located in the middle basin of Redwood Creek, had the highest values for MWAT

Fig. 4. Maximum weekly maximum temperatures, 1997 to 2003. Coho (*Oncorhynchus kisutch*) presence and absence thresholds are derived from studies in a nearby river basin, the Mattole (Welsh et al. 2001).

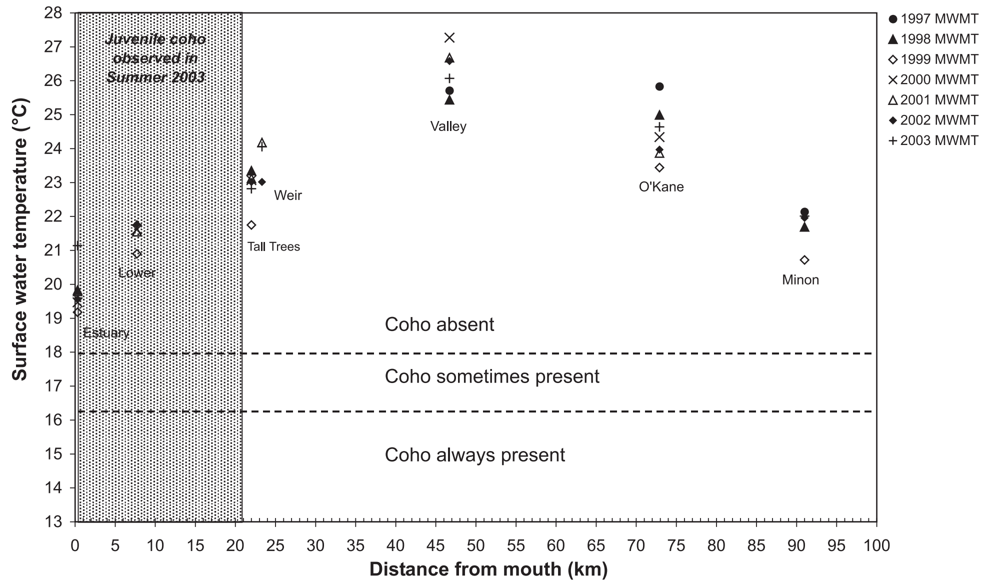
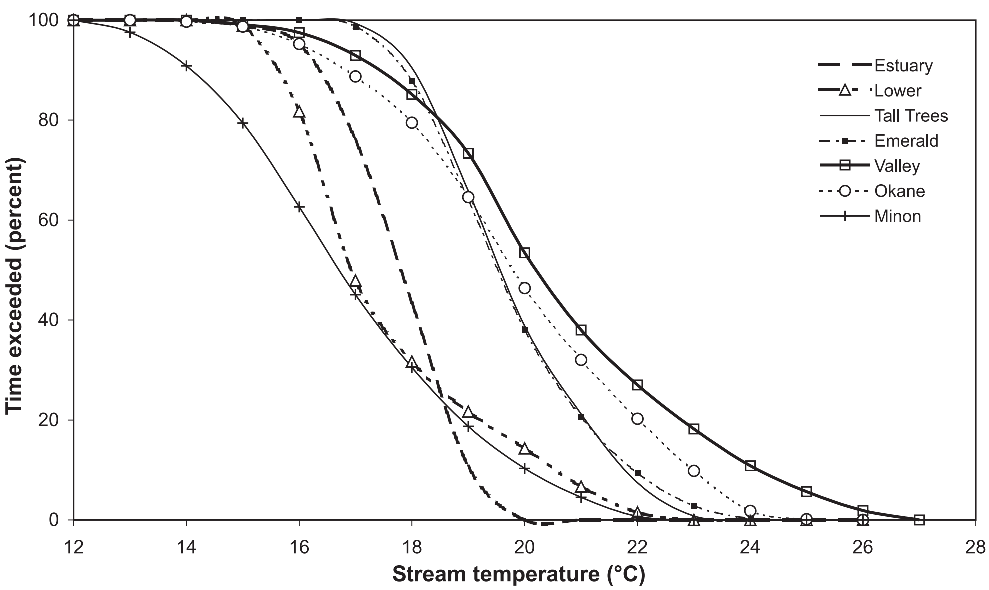


Fig. 5. Cumulative frequency distributions for July and August 2002 showing the total time that a given stream temperature was exceeded during these months. These distributions are typical for all the years studied.



and MWMT. MWMT values increased sharply upstream of Redwood Creek at Tall Trees Grove (Tall Trees, rkm 22) (Fig. 4), which coincides with the upstream extent of coho documented during the 2003 presence–absence survey. MWAT also increased between the lower Redwood Creek (rkm 7.7) and the Tall Trees monitoring sites. Minon and Lower have the lowest temperature values, except for the Redwood Creek estuary (Estuary, rkm 0.3), which is moderated by inflow from the ocean.

Duration of exposure to high temperatures

Upper Redwood Creek (Minon) had the longest duration of cool temperatures (<18 °C) and Valley had the longest duration of high temperatures (>20 °C) (Fig. 5). These cumulative frequency distribution patterns are typical of the period of record (1997–2003). The temperature distributions for Tall Trees and Emerald were virtually the same, which is not surprising because they are located within 1.3 km of each other. Although these two sites exhibit less time at the highest temperatures than Valley and O'Kane, they also had less time at cool temperatures (<18 °C). Lower and Minon had similar exceedence curves for temperatures >18 °C, but Minon experienced a longer time span at cooler temperatures. Finally, Estuary had the most modulated temperature regime, with temperatures ranging from 16 °C to 20 °C most of the time.

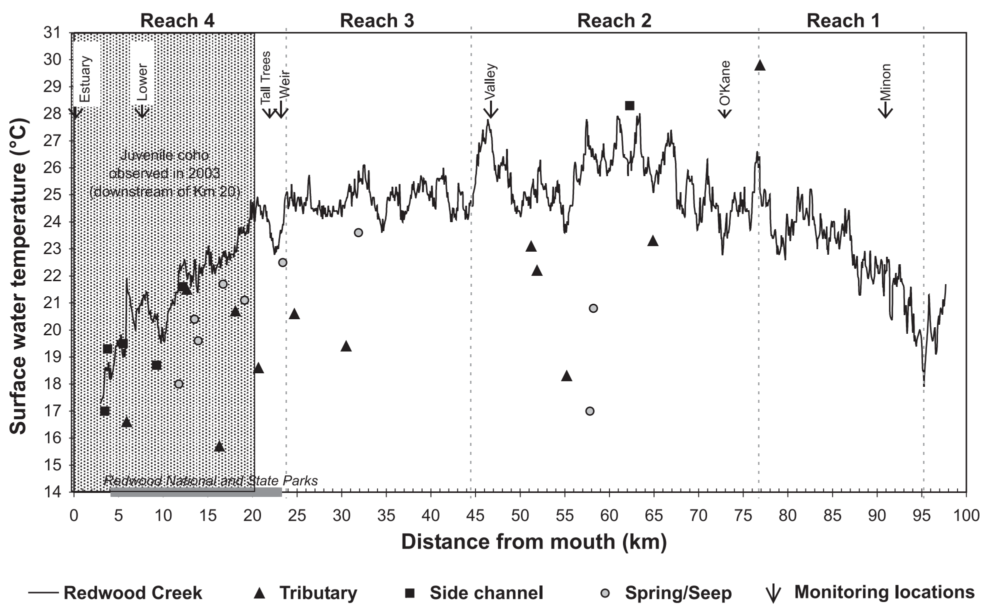
The cumulative frequency–distribution curves represent the total number of hours that a given temperature was exceeded during the summer season. These curves can be examined in

Table 3. Geometric means of duration of stress intervals for temperatures exceeding 18, 20, 22, and 24 °C and frequency of stress intervals.

	Duration of stress intervals (h)				Frequency of stress intervals			
Site	>18 °C	>20 °C	>22 °C	>24 °C	>18 °C	>20 °C	>22 °C	>24 °C
Estuary	7.7ab	4.6a	1.0a	ND	148	20	1	ND
Lower	8.4b	4.4a	2.4ab	ND	223	178	11	ND
Tall Trees	26d	9.2b	3.6b	ND	98	237	107	ND
Emerald	26d	9.8b	4.3bc	2.2a	58	166	101	13
Valley	23c	11c	5.9d	2.8a	107	222	225	180
O'Kane	17c	9.0b	5.3cd	3.5b	163	219	133	27
Minon	5.7a	3.6a	1.8a	ND	174	68	12	ND

Note: Sites not sharing a common letter were statistically different from one another ($p < 0.05$). Sites with increasing stress interval durations are classified by alphabetically increasing letters. Sites indicated with ND had no stress intervals >24 °C. A stress interval is the number of consecutive hours over a specific high temperature.

Fig. 6. Median surface water temperature based on thermal infrared (TIR) imaging along Redwood Creek. Some surface flow temperatures in tributaries were recorded by the TIR imagery. Note that the locations of in-stream monitoring sites were distributed to detect the main temperature trends in the basin. (Modified from WSI (2004).)



finer detail through the tabulation of stress intervals, which examines total consecutive hours exceeding a specific temperature. Statistical comparisons of stress intervals at the seven sites are summarized (Table 3). As with the daily minimum and maximum temperature models, a repeated-measures model based on temporal correlations exponentially over the sequence of stress intervals was superior to a model assuming no temporal correlations for >18, >20, >22, and >24 °C stress temperatures (AIC difference ≥100). The exposure to consecutive hours of high temperature was similar in the uppermost and downstream reaches of Redwood Creek. There were no statistical differences detected in the durations of >20 and >22 °C stress intervals between lower Redwood Creek (coho-bearing reach) and the Minon reach (no coho present). However, there was a difference between these two reaches for stress intervals >18 °C, where Minon had statistically shorter stress intervals. Neither station had any stress intervals of >24 °C. In contrast, stations in intervening reaches (Tall Trees, Emerald, Valley, and O'Kane) had significantly longer >18 and >20 °C stress intervals than the Lower or Minon stations. The Valley and O'Kane sites also had longer >22 °C stress intervals than the Lower and Minon stations. It is interesting to note that the Tall Trees and Emerald sites had significantly longer intervals of >18 °C than O'Kane (so less nighttime cooling), even though the MWATs and MWMTs are consistently higher at O'Kane.

TIR imaging

Surface water temperature data collected through TIR imaging in Redwood Creek is summarized (Fig. 6). The thermal profile of Redwood Creek generally increases from the headwaters to the middle part of the basin and then cools as it approaches the coast. This thermal signature has also been observed on the nearby Mattole River (Russ Faux, Watershed Sciences Inc., 230 SW 3rd Street, Corvallis, OR 97333, USA, personal communication). Water temperature varied on a shorter scale as well, e.g., changing more than 1 °C within a kilometre of the stream channel in several areas. Many such changes were associated with the inflow of tributaries or springs. Based on the TIR data for 29 July 2003, Redwood Creek can be divided into four main reaches that showed similar temperature characteristics (Fig. 6): reach 1, warming zone, water temperature in Redwood Creek increased from 17.9 °C in the headwaters to 26.5 °C downstream at rkm 76; reach 2, hot zone, the middle basin, where surface water temperatures ranged from 23 °C to 28 °C, exhibited the highest water temperatures of the survey; reach 3, warm zone, stream temperatures cooled slightly in the next 20 km, where the average surface water temperature was 24.8 °C; reach 4, cooling zone, in the downstream-most reach of Redwood Creek, closer to the ocean, stream temperatures cooled. The highest number of cool tributaries, springs, and seeps were also detected in this reach.

Discussion

TIR remote-sensing technology successfully provided spatially continuous stream temperature data for a 90 km reach of river in a large basin. This technology enabled stream temperature assessment across mixed ownership and inaccessible areas of the Redwood Creek basin. The longitudinal temperature profile from TIR imagery provides a clear snapshot of the current thermal regime in Redwood Creek and a baseline for monitoring future changes in stream temperature. Although TIR data for Redwood Creek provided a surface temperature profile at a limited temporal scale (one afternoon), the survey supplemented a 7-year temperature monitoring program conducted at a more limited spatial scale (seven sites). The TIR data identified four general stream reaches with differing thermal characteristics, which corroborated patterns detected by the continuous in-stream monitoring. Small cool-water seeps, springs, and side channels within the warmer river channel were also identified with TIR imagery.

TIR longitudinal profile data were also used to evaluate the adequacy of locations of long-term temperature monitoring sites. In-stream data loggers provide point data along the length of Redwood Creek, but TIR data integrate the spatial distribution and general thermal characteristics of the creek. We compared the location of stream temperature monitoring sites with the spatial distribution of water temperature throughout the basin from the TIR survey, which indicated that the current in-stream monitoring locations provide an adequate representation of stream temperature distribution in Redwood Creek. An additional data logger near rkm 60 would help better define the thermal regime in the hot zone, however.

The longitudinal temperature data revealed that Redwood Creek reaches its maximum temperature in the middle basin and becomes cooler farther downstream, unlike many rivers reported in the literature (Allan 1995). Lewis et al. (2000) demonstrated that the highest daily maximum temperatures in coastal streams in northern California were less than those in inland streams. In Redwood Creek, it is probable that coastal fog, old-growth redwood trees in the riparian zone, and an abundance of cool-water tributaries and seeps in the lower basin all contribute to the cooling trend there, but the relative importance of each of these factors is a subject for further research.

A comparison of thermal regimes at several sites in Redwood Creek shows some limited recovery of cool temperatures in upper Redwood Creek. From 1953 to 1959, before widespread basin disturbances, the maximum summer water temperature measured at Redwood Creek at O’Kane was 22 °C. Following severe floods, channel aggradation, and extensive timber harvest in the 1960s and 1970s, maximum water temperatures increased and peak summer water temperatures between 29 and 33.5 °C were measured in the period from 1975 to 1980. Since 1997, however, the peak temperatures in July and August have decreased to between 24.9 and 26.8 °C and the average daily maximum temperature decreased almost 3.5 °C to 22 °C. Some physical characteristics of the channel are recovering in this reach, based on the return to former streambed levels after aggradation (Madej and Ozaki 1996) and the re-establishment of riparian vegetation and canopy closure over Redwood Creek (Urner and Madej 1998), which may be contributing to the thermal recovery.

Our monitoring indicates that thermal recovery may be more complete in upper Redwood Creek (Minon) than at sites farther downstream. Thermal regimes differed markedly in the middle basin compared with the lower and upper basin. We used several metrics to compare the temperature regimes in upper Redwood Creek (Minon) and mid-upper Redwood Creek (O’Kane), where coho are absent, with lower Redwood Creek (Lower), where coho are still found. Daily maximum temperatures were not significantly different between Minon and Lower, and Minon had significantly lower minimum temperatures than Lower. Based on this analysis, we do not believe that summer water temperature is a limiting factor to juvenile coho rearing in the upper (Minon) reach.

In contrast, even though the temperature regime at O’Kane has improved since 1978, average maximum water temperature is significantly higher at O’Kane than at Lower, and MWMTs and MWATs are consistently higher at O’Kane. The duration of stress intervals was significantly longer at O’Kane than at Lower. The intervening reach between O’Kane and Tall Trees was significantly warmer than either Minon or Lower in terms of daily maxima and duration of stress intervals, and MWATs and MWMTs were also higher here. In addition, TIR data documented water temperatures of >22 °C for this 50 km reach. In the middle basin, MWATs and MWMTs for several years were >21.8 and >25 °C, respectively. Studies by Welsh et al. (2001) on tributaries of the Mattole River, California, suggest that streams with MWMT greater than 18.1 °C or MWAT greater than 16.8 °C may restrict the presence of juvenile coho salmon. (Coho salmon in Redwood Creek and the Mattole River are grouped within the same Evolutionary Significant Unit). Although the main channel of Redwood Creek is accessible to salmon and steelhead for most of its length and historically coho ranged throughout most of Redwood Creek, juvenile coho salmon are noticeably lacking in the middle and upper basins. High temperatures in the middle basin likely restrict juvenile rearing habitat there.

Many studies evaluate stream temperature regimes by only using daily and weekly means and maxima. Although these metrics give a useful snapshot of thermal conditions, an analysis of duration of high temperatures revealed additional thermal patterns of interest to us. For example, Redwood Creek at Tall Trees, despite having cooler maximum temperatures than the hot middle reach, exhibited longer durations of moderately high temperatures (>18 °C) than the middle reach (Valley) and so represents a different type of thermal stress for fish. Minon also had significantly shorter durations of stress intervals (consecutive hours above 18, 20, and 22 °C) than Lower. The difference in patterns between MWMT and stress interval data suggests that duration of elevated temperatures should be considered in addition to daily maximum and average temperatures to more fully represent water temperature regimes. The relative importance of short durations of high temperatures versus longer durations of moderately high temperatures on fish physiology in Redwood Creek is not known, and we encourage the use of additional metrics, such as cumulative distribution curves and stress intervals, to assess duration characteristics of thermal regimes.

The coho presence–absence surveys indicated that juvenile coho rearing is currently limited to the downstream-most section of Redwood Creek, and less than 20% of the main channel currently supports young coho during the summer. Stream temperature monitoring indicated that there is a sharp decrease in the MWAT, MWMT, and maximum daily water temperature on the lower river between rkm 22 and rkm 7.7 across all years. In addition, the TIR profile showed the greatest thermal complexity in the downstream-most reach of Redwood Creek, where many cools springs, seeps, side channels, and tributaries were measured.

During the last 5 years, no juvenile coho have been caught at the downstream migrant trap in Redwood Valley (rkm 53.0), indicating no use by juvenile coho upstream of the trap site (Sparkman 2004). TIR data indicate that Redwood Valley is the hottest reach in Redwood Creek. In-stream temperature monitoring supports this conclusion, and since monitoring began in 1997, Redwood Valley has had the highest maximum daily water temperatures, MWATs, and MWMTs of all the monitoring sites along the entire length of the creek. During 2004, Sparkman (2004) caught YOY coho salmon at the lower downstream migrant trap (rkm 6.4) on Redwood Creek every month from April to July. This indicates that lower Redwood Creek and the estuary may still provide important rearing habitat for juvenile coho salmon. Unfortunately, there is limited information on coho distribution in the Redwood Creek basin through time. Nevertheless, we have shown that a headwater reach (O'Kane) that was historically cool and then experienced increased temperatures for at least 5 years has begun to thermally recover, and upstream of that reach (at Minon), conditions are similar to those in a coho-bearing reach of stream. However, the intervening 50 km reach of stream has summer water temperature several degrees warmer than what is reported to be acceptable for coho in the nearby Mattole River basin (Welsh et al. 2001). The only reach that currently supports coho is the downstream-most 20 km of the 100 km long Redwood Creek. Based on this study and the Mattole River coho distribution data, we suggest that a thermal restriction may be reducing the historical range of rearing for juvenile coho for about three-quarters of the length of Redwood Creek.

There are several limitations to this study. Although TIR remote sensing can map surface water temperature, it cannot be used as a tool to identify thermally stratified pools, which may be several degrees cooler at depth. Past studies have shown that although few in number, cold pools exist in lower Redwood Creek (Moses 1984; Ozaki 1988; Keller et al. 1995) and provide important coldwater refugia for salmonids during periods of thermal stress (Nielsen et al. 1994). For the past couple of years, juvenile steelhead have been observed using cooler thermal areas in Redwood Valley (Valley) during periods of high water temperature (Michael Sparkman, 50 Ericson Court, Arcata, CA 95521, USA, personal communication). Some of the most interesting cool-water interactions occur along the channel banks. Unfortunately, with TIR data, the riparian vegetation commonly obscures the channel edges where cool groundwater seeps and springs may emerge. Small areas (<3 m^2) of groundwater seeps or cool upwelling are nondetectable at the scale of the TIR flight used in this study. Likewise, in-stream monitoring by probes emplaced in the main flow will not detect small cool-water sources. As a result, small cool-water refugia may exist in warm reaches of Redwood Creek, but these must be quantified by a different method

Based on the results of this study, stream temperature appears to be a dominant factor controlling distribution of juvenile coho salmon. Nevertheless, past land use and large floods caused extensive channel aggradation, which adversely affected aquatic and riparian habitat and destroyed juvenile rearing habitat in Redwood Creek. Timber harvest and stream bank erosion resulted in a loss of riparian trees and habitat. Surveys of longitudinal profiles of the lower river in 1977 indicated that the channel bed was filled in with sediment and lower Redwood Creek was flat and featureless after large storms in 1964 and the early 1970s. Pool depths and frequencies have subsequently increased (Madej 1999). Although aquatic and riparian habitat in Redwood Creek is recovering, there are still lingering effects such as the lack of large riparian trees to provide both stream shading and a source for in-stream wood and the lack of functional large woody debris in the channel to scour pools and provide cover and channel complexity (California Resources Agency 2005). The lack of high-quality rearing habitat, large wood, and channel complexity may also contribute to the limited upstream distribution of coho.

Other possible factors may affect the distribution of coho in the Redwood Creek basin. The influence of fish hatchery operations in Prairie Creek, a tributary entering Redwood Creek near its mouth, from 1894 to 1993 is not known. The Prairie Creek hatchery produced coho salmon from 1924 to 1993, with the exception of 1945–1960. Hatchery operations may have introduced higher numbers of coho to the basin and coho runs in Redwood Creek may have been artificially increased. Presently, no invasive or exotic fish species exist in Redwood Creek. Nevertheless, there may be shifts in the native fish communities in response to changing channel conditions and warmer stream temperature regimes.

In addition, lower Redwood Creek was severely altered following the construction of flood control levees in 1968. Historically, Redwood Creek near its mouth meandered across a wide floodplain. The levees channelized the downstream-most 5 km of channel into a narrow straight chute, isolating the river from its floodplain. Consequently, access to favorable backwater and alcove habitat by coho in this reach was eliminated. Because the riparian zone along two-thirds of Redwood Creek has been converted from a conifer-dominated system in 1947 to a deciduous system (Urner and Madej 1998), nutrient and invertebrate prey availability has probably changed, as suggested by Murphy and Meehan (1991). Turbidity levels in Redwood Creek frequently exceed 300 nephelometric turbidity units (NTU) during winter flows (R. Klein, RNSP, 1655 Heindon Road, Arcata, CA 95521, USA, unpublished data). Bisson and Bilby (1982) reported that juvenile coho salmon avoided water with turbidities that exceeded 70 NTU. High winter turbidity levels may affect the ability of juvenile coho to feed and thus affect their growth, but these factors have not been quantified. Future research will examine the influence of such factors on coho distribution. Nevertheless, our study highlights the importance of temperature monitoring over a long time period along the entire length of river, as well as the need for integrative studies incorporating bioenergetics and physiology with temperature monitoring and modeling.

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